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Super Multi-View 3-D Display System using Vibrating Scanner Array(ViSA)

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In this paper, we propose a super multi-view(SMV) 3-D display system using a vibrating scanner array (ViSA). The parallel beam scanning using a vibrating scanner array is performed by moving back and forth an array of curvature-compensated mirrors attached to two vibrating membranes. The parallel laser beam scanner array can replace the polygon mirror scanner which has been used in the SMV 3-D display system based on the focused light array(FLA) concept. The proposed system has great advantages in the sense that it requires neither huge imaging optics normechanical scanning parts. Some mathematical analyses and fundamental limitations of the proposed system are presented. The proposed vibrating scanner array, after some modifications and refinements, will replace polygon mirror-based scanners in the near future.

I. INTRODUCTION

While most information is communicated through 2-D images or printed words, most data channels transfer only a series of data elements. Therefore, to manipulate the information for either transmission or reception, a 2-D image space must be transformed to or from a single function of time. This is what scanners do, and we can say that, in our information age, scanning is as fundamental to information transfer as vision is to perception. Scanners can serve to both input and output information.

There are several types of optical scanners. The most widely used scanner is a galvanometer scanner, due to its easy configuration and cheap price. Polygon mirror scanners that are used in laser printers also provide very good scanning quality. Bar code readers harness the holographic scanning method. Acoustooptic and electrooptic scanners are often used in systems that require accurate scanning quality. Optical disk scanners are used in storage systems such as CD-ROMs. Aside from the applications that are mentioned here, scanning systems also play very important roles in implementing 3-D display systems.

3-D display systems (See [1], [2], [3], [4] and references therein.)can be implemented in various ways. The fundamental mechanisms for implementation can be classified into three categories: spatial multiplexing; time multiplexing; and angular multiplexing. 3-D display systems utilizing optical plates such as lenticular screen, parallax barrier, and holographic screens that are used to generate viewing zones belong to the spatial multiplexing scheme. Field-sequential binocular stereoscopic videos with polarizing glasses or LCD shutters are of the time-multiplexing type. The 3-D display system based on FLA(Focused Light Array) may be classified as in the angular multiplexing category.

3-D display systems that utilize spatial-multiplexing scheme suffer from the resolution limitations of the display devices as the number of images to be presented increases. An electroholographic 3D display system [5, 6, 7]using a polygon mirror and galvanometer scanner or LCD records and displays the data based on a spatial multiplexing, and thus suffers from the resolution limitation problem of the display devices. On the other hand, systems based on the time-multiplexing scheme have to solve the speed limitations of electronics and refreshing speed of CRT or LCD projectors if one wants to increase the number of images for alleviate the unnaturalness of discrete parallaxes and provide better viewing zones. Multi-view 3D display systems with CRT projectors and holographic screens [8] are utilizing basically time-multiplexing, and thus speed of elec-

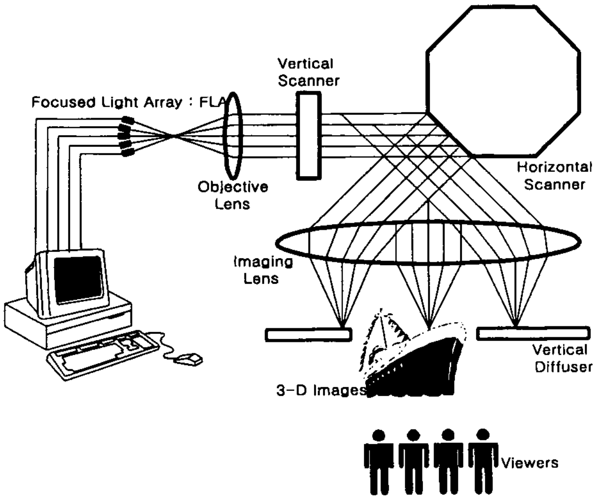

FIG. 1. Super Multi-View 3-D Display System Based on FLA(Focused Light Array).

tronics and switches are limiting factors. Even though spatiotemporal multiplexing [9] can increase the number of images that can be presented by a factor of 2, there exists a fundamental limitation in that the number of images cannot increase dramatically without any special breakthrough technologies.

The concept of Focused Light Array (FLA) [10] can solve these problems, as shown in Fig. 1, by presenting simultaneously as many images as one wants, superimposed but separated by less than the pupil size. This is called the Super Multiview(SMV) region. An implementation of the FLA using a galvanometer and a polygon mirror scanner has been demonstrated by TAO with the simultaneous scanning of the 45 images. However, polygon mirrors and galvanometers have their own disadvantages in that the scanning requires mechanical rotation which is delicate with respect to external physical impact. More than that, the FLA system requires that the imaging optics should be as large as the size of the screen and viewing angle. These problems can be solved by using an array of curvature-compensated parallel laser beam scanning method that has been recently presented in several places such as [11], [12], and [13].

In this paper, we present a new implementation of a supermulti-view 3D display system using the parallel laser beam scanning method. The parallel scanning is performed by moving back and forth an array of curvature-compensated mirrors attached to vibrating membranes. In Sec. 2, we characterize some aspects of galvanometer and polygon mirror scanners. Explanation of the operating principles of the proposed system is given in Sec. 3. Sec. 4 demonstrates a specific design example of the vibrating scanner array. Finally, conclusions are given in Sec. 5.

II. CHARACTERIZATION OF GALVANOMETER AND POLYGON MIRROR SCANNERS

Galvanometer scanners are used extensively in laser scanning systems. From an optical point of view, they have several advantages. The scanning mirror can rotate about an axis in the plane of mirror. The mirror can then be located at the entrance pupil of the lens system and its position does not move as the mirror rotates. Moreover, the $F-\theta$ condition is often not required, because the shaft angular velocity of the mirror can be controlled electronically to provide uniform spot velocity. Finally, galvanometer systems are suitable for XY scanning. The principal disadvantage of galvanometer scanners is that they are limited in writing velocity. Galvanometer scanners provide the easiest way to design an XY scanner. The two mirrors, however, have to be separated from each other, and this means that the optical system has to work with two separated entrance pupils, with considerable distance between them. This, in effect, requires that the lens system be aberration-corrected for a much larger aperture than the laser beam diameter. A system demanding large aperture and field then will have different degrees of distortion correction for the two directions of scan.

Polygon and holographic scanners are mainly used for applications which require severe uniformity of scanning velocity, sometimes as low as 0.1%, with addressability of a few microns, and high-speed scanning velocities. In the design of lens systems for polygons, some optical effects must be considered. These include: bow; beam displacement; and cross scan error.

The incoming and exiting beams must be located in a single plane which is perpendicular to the polygon rotation axis. Errors in achieving this condition will displace the spot in the cross-scan direction by an amount which varies with the field angle. This results in a curved scan line, called bow. The spot displacement E as a function of field angle is given by the equation

$$E = F \sin\alpha \left[\frac{1}{\cos\theta} - 1\right], \tag{1}$$

where F is the focal length of the lens, θ is the field angle, and α is the angle between the incoming beam and the plane that is perpendicular to the rotation axis.

The optical axis of the focusing lens should be coincident with the center of the input laser beam, referred to as the feed beam. Any error will introduce bow. The bow introduced by the input beam not being in the plane perpendicular to the rotation can, however, be compensated, to some extent, by tilting the lens axis.

A second peculiarity of the polygon mirror scanner is that facet rotation occurs around the polygon center rather than facet face. This causes a facet displacement of the collimated beam as the polygon rotates. This displacement of the incoming beam means that the lens must be well corrected over a larger aperture than the laser beam diameter.

The polygons usually have pyramidal errors in the facets as well as some axis wobble. These cause cross-scan errors in the scan line. These errors must be small, for the eye is extremely sensitive in spotting them. Some printing systems achieve more than 1000 dots/inch performance. This means that the maximum cross-scan error in this case should be much less than 25 μm. A system with no cross-scan error correction using a 700 mm focal length lens, would require pyramid error no larger than 2 arc seconds. Three ways to correct for the cross-scan error in polygons are the use of (1) cylindrical lens, (2) anamorphic beam on the facet, and (3) retroflective prisms.

III. OPERATING PRINCIPLES OF THE PROPOSED SYSTEM

To explain the operating principles of the proposed system, we refer to Fig. 2. The video signals modulate the laser diode array and the multiple light rays are incident on the corresponding curvature-compensated mirrors of the mirror array. By moving the mirror array back and forth, all the light rays are reflected in a parallel manner to hit the diffuser screen simultaneously. Each of the beams is scanned at the same time by using curvature-compensated reflector array as shown in the circle of Fig. 2. The reflecting mirror compensates the scanning speed at the screen to guarantee uniform intensity of the scanned light.

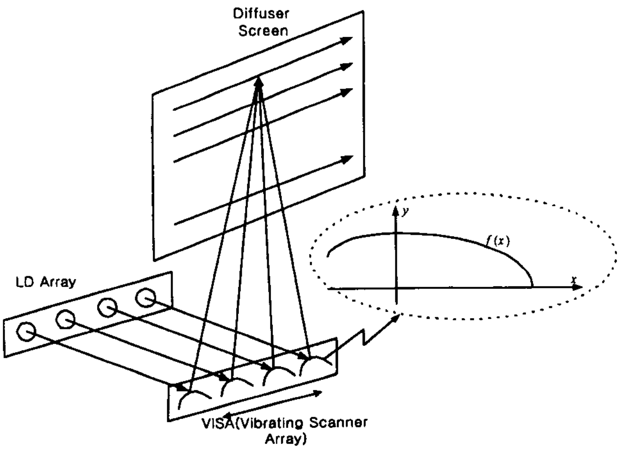

FIG. 2. Super Multi-View 3-D Display System Based on Parallel Laser Beam Scanning.

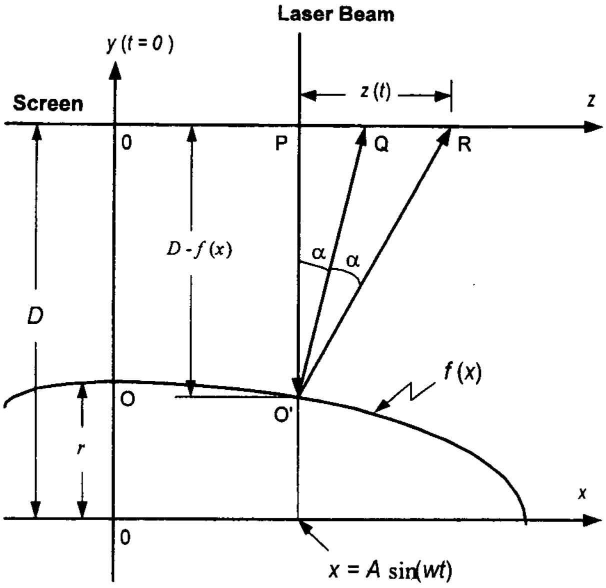

FIG. 3. One Mirror Element of the Parallel Beam Scanner with Curvature Compensated.

Fig. 3 shows one mirror element, shown in the circle of Fig. 2,through which we can determine the shape function $f(x)$. It also describes the mode of the laser beam reflection and scanning mechanism. We let the curve of the mirror attached to a sinusoidally vibrating actuator moving in the $+x$ and $-x$ axis be the function $f(x)$ that is to be determined. The distance between the screen and the reflecting mirror is set to be D.

The center of the mirror is assumed to be located at $x = 0$,and the height (r) is $r = f(0)$. At time $t = 0$, the laser beam is incident on the point O, and we want the beam to be reflected back through exactly the same path as it gets in. This requires that $f'(0) = 0$. After t seconds, the mirror moves to the left by the amount $x = A\sin(wt)$, where A is the maximum deviation of the mirror that can move from the origin, and the laser beam hits the point S. Then the beam is reflected to hit the screen at the position R according to the reflection law, where α is the angle between the vertical line and the normal line at the point S. From a simple geometric analysis and reflection law, we can get the position $z(x)$ of the reflected beam at the screen as

$$\begin{aligned} z\,(x) &= [D - f(x)]\,\tan 2\alpha \\ &= 2\,[D - f(x)]\frac{f'(x)}{[f'(x)]^2 - 1}, \end{aligned} \tag{2}$$

Now, the point $z(x)$ that the reflected light hits over the screen needs to move at a certain constant speed such that the intensity is uniform everywhere over the scanning line of the screen. Therefore, the function $z(x)$ has to be evaluated at $x = A\sin(wt)$ to produce

$$z(t) = \left[\frac{2\,\{D\ -\ f(A\ \sin wt)\}\ f'(A\ \sin wt)}{[f'(A\ \sin wt)]^2\ -\ [wa\ \cos(wt)]^2} \right]\ wA\ \cos(wt), \tag{3}$$

and the uniform intensity is guaranteed if the derivative of the function$z(t)$ with respect to t is set to be a constant C.

Our goal is to find the function $f(x)$ by solving the differential equation $z'(t) = C$, where t is evaluated at $t = \frac{\sin^{-1}(x/A)}{w}$. Even though it is not impossible to find the derivative of the function $z(t)$, it is a tedious and time-consuming job to find the exact solution of the differential equation in this paper. What we can easily guess, though, is that the differential equation is highly nonlinear. The Runge-Kuta method did not work for this case. To obtain a reasonable result for $f(x)$ for the curvature-compensated mirror, we simplify the nonlinear problem to have a linear differential equation. The result of the linearization process of the nonlinear differential equation for analyzing the curvature-compensated mirror is shown in Fig. 4.

As shown in Fig. 4, the laser beam hits the point N at time$t = 0$ and is reflected back to hit the point M, where the path of the reflected beam is the entrance path. At $t = t_1$, the point t_1 moves to point O, and the beam will hit the point Q on the mirror. At this point we want the reflected beam to hit the point T which is separated by p from the point P, where p is the resolution of the screen that users can determine for their specific applications. The relationship between p and α_1 can be written as

$$[D\ -\ f(x_1)]\ \tan\alpha_1\ =\ p. \tag{4}$$

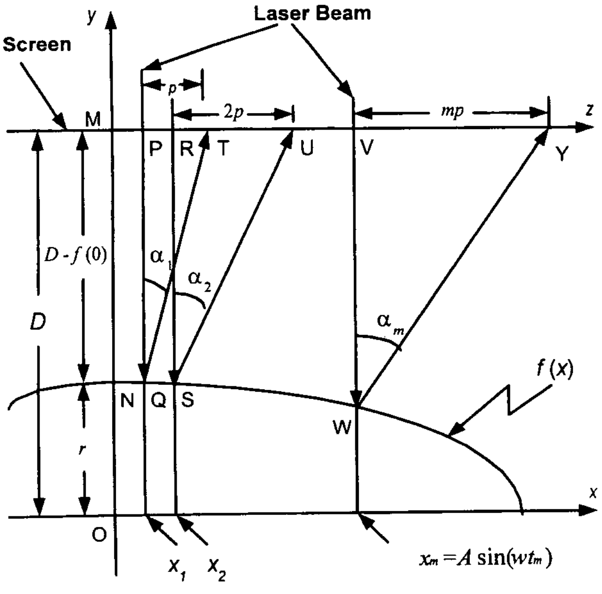

FIG. 4. Linearization of the Nonlinear Problem.

At $t = t_2$, the point x_2 moves to point O, and the beam hits the point Sto be reflected to hit the point U. For uniform speed of scanning, we want the distance between R and U to be $2p$ to give the relation

$$[D\ -\ f(x_2)]\ \tan\alpha_2\ =\ 2p. \tag{5}$$

Generalizing this procedure at $t = t_m$, the point x_m moves to point O, and the incident beam hits the point W. Then it is reflected to hit the point Y which is separated by mp from the point V. This can be written as

$$[D\ -\ f(x_m)]\ \tan\alpha_m\ =\ mp, \tag{6}$$

where

$$\tan(\alpha_m)\ =\ \frac{-2\ f'(x_m)}{1\ -\ [f'(x_m)]^2}. \tag{7}$$

Rewriting Eqs. (6) and (7), we obtain

$$mp\,[1\ -\ \{f'(x_m)\}^2]\ =\ -\ 2\ f'(x_m)[D\ -\ f(x_m)]. \tag{8}$$

As we expected, this is a nonlinear differential equation. If we assume, however, that the function $f(x)$ does not change too much in the vibrating range compared with the distance D, then we can write $D - f(x_m)$as a constant $D - r$, and we can simplify this nonlinear equation to a linear equation by solving the following quadratic equation given by

$$mp\,[f'(x_m)]^2\ -\ 2\,[D\ -\ r]f'(x_m)\ -\ mp\ =\ 0. \tag{9}$$

Recall that the movement of the membrane is symmetric. Therefore, it is sufficient to consider only the right hand side of the mirror, and under this consideration, the sign of the slope $f'(x_m)$ should be negative to give

$$f'(x_m)\ =\ \frac{(D\ -\ r)\ -\ \sqrt{(D\ -\ r)^2\ +\ m^2p^2}}{m\ p}. \tag{10}$$

Finally, we can find the linear equation $f_m(x)$ at the point x_m as

$$f_m(x)\ =\ A_m x\ +\ B_m, \tag{11}$$

where A_m is given by Eq. (10) with $A_m = 0$, and B_m will be determined iteratively from the initial condition of the mirror, that is, $B_0 = r = f_0(0)$, and

$$f_m\ \left(\frac{x_m\ +\ x_{m-1}}{2}\right)\ =\ f_{m-1}\ \left(\frac{x_m\ +\ x_{m-1}}{2}\right). \tag{12}$$

From Eqs. (10),(11), and (12), we can design each mirror of our parallel beam scanners as well as the screen size. In Section 5, we will show some computational results for a specific scanning system.

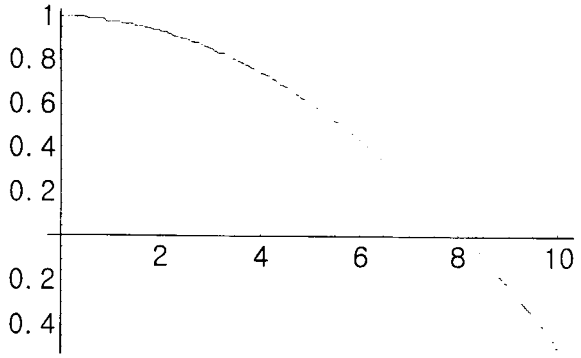

FIG. 5. The shape function $f(x)$ with $A = 10$ and $r = 1$.

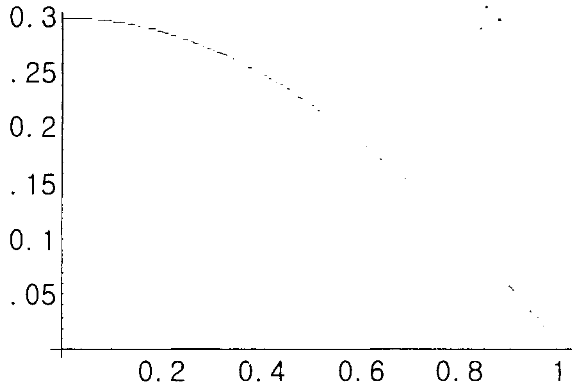

FIG. 6. The shape function $f(x)$ with $A = 1$ and $r = 0.3$.

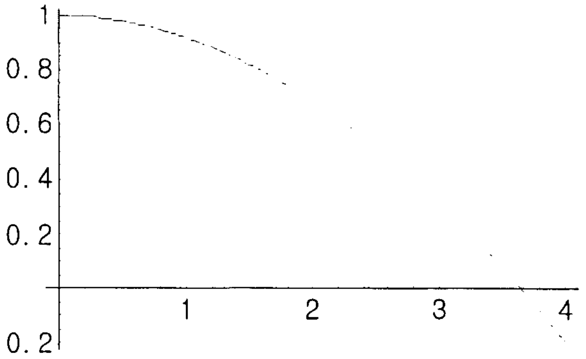

FIG. 7. The shape function $f(x)$ with $A = 4$ and $r = 1$.

IV. EXAMPLES OF SCANNER ARRAY DESIGN AND COMPUTATIONAL RESULTS

As an example of a parallel beam scanner, we have selected the screen that can be used as a practical 3-D display terminal. In other words, the size of the screen has been chosen to be 400 mm × 300 mm. Since we want the terminal to be able to support the VGA mode (640 × 480), the resolution of the screen becomes $p = 400/640 = 0.625$ mm. The distance between the scanner and the screen has been set to be $D = 100$ mm. Based on these fixed parameters and equations given in Eqs. (10) to (12), the computer computations for three different cases of the remaining parameters with (1) $A = 10$, $r = 1$, (2) $A= 1$, $r = 0.3$, and (3) $A = 4$, $r = 1$ have been performed to find the curvature function $f(x)$, and the results are shown in Figs. 5, 6, and 7,respectively. From these figures, we can see that they are simply scaled down for each case. The ratio of the depth of the mirror to the maximum deviation was always 3. This means that we can design the parallel beam scanner as small as we want, depending upon the types of vibrating membranes. The beam width of the laser will be the only factors that will affect the performance of the system.

V. CONCLUSION

Scanning systems play important roles in 3-D display systems. Especially, polygon mirror and galvanometer scanners have been used for electroholographic3-D display systems as well as super multi-view 3-D display systems with the FLA concept. However, the polygon mirror scanners are operating mechanically, which inevitably makes them delicate with respect to external physical impacts. Moreover, the FLA system with the polygon mirror scanner requires large imaging optics whose size is proportional to the viewing angle as well as the number of views that we want to impose.

In this paper, we proposed a super multi-view 3D display system using a vibrating scanner array which replaces the use of the polygon mirror scanner. The proposed system has a great advantage in that it does not require huge imaging optics, and that the mechanical scanning part has been replaced by electrical scanning. The parallel scanning is performed by attaching an array of curvature-compensated mirrors to two sinusoidally vibrating membranes. Mathematical analyses for finding the curvature function of the mirror are presented.

Based on these analyses, some computer computations have been performed to verify the concept of the proposed system by demonstrating sample designs for the case when the size of the screen is 400mm × 300 mm with 640 × 480 resolution, and the distance between the parallel beam scanner and the screen has been set to be $D = 100$ mm.

With these fixed parameters and different cases of maximum deviation A and the initial height of the mirror r, the computer computational results have shown that, in all the cases, the shapes are simply scaled down, and the ratio of the depth of the mirror to the maximum deviation was always 3. This means that we can design parallel beam scanners as small as we want, depending upon the types of vibrating membranes. The beam width of the laser will also be a factor that will affect the performance of the system. Some analyses on these factors will be presented in the near future.

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